Development of Gasdynamic Probe for Total Temperature Measurement in gases

K Sathiyamoorthy[1], Souren Misra[2], Srinivas J[1], Baskaran M[1] and Manjunath P[1]
[1]Propulsion Division, CSIR-National Aerospace Laboratories, Bangalore – 560017.
[2]Department of Aerospace Engineering, Indian Institute of Science, Bangalore – 560012
[1]sathy_cim@nal.res.in

Abstract—**Total temperature measurement in exhaust stream of air breathing engines like Ramjet, Scramjet and Aircraft afterburners is a challenging task as the temperatures in such engine exhausts are above 2200K. Thermocouples for such high temperature measurement suffer from oxidation and are expensive. Optical method for this application requires high level of expertise and is expensive. Gasdynamic probe is a special type of water cooled probe and can give total temperature of the flow by measuring the flow parameters like total pressure and mass flow through the probe nozzle. The probe is very simple in construction and can be made at a low cost. This paper describes about the development of a Gasdynamic probe and calibration for probe constant for various flow parameters.**

Keywords: **Total Temperature Measurement, Pneumatic Probe, Gasdynamic Probe, Scramjet.**

NOMENCLATURE

R	Gas constant
γ	Ratio of specific heat
P_{o1}	Total pressure at inlet to the probe nozzle (first restriction)
T_{o1}	Total temperature of the gas to be measured (Total temperature inlet to the probe nozzle)
A_{nt}	Nozzle throat area
A_o	Orifice area (second restriction)
C	Probe constant (m_a /m_t)
m_a	Actual mass flow rate of gas through nozzle and measured through orifice meter.
m_t	Theoretical mass flow rate of gas through nozzle
P	Static pressure orifice meter upstream
T	Static temperature orifice meter upstream
ΔP	Differential pressure across orifice meter
C_d	Nozzle co-efficient of discharge
d_{nt}	Diameter of the Nozzle throat (2.35 mm)
d_o	Diameter of the orifice plate (5.98 mm)

1. INTRODUCTION

The gasdynamic probe consists of a small sonic nozzle followed by a cooling chamber, a precision orifice meter and a shut off valve. The entire probe is water cooled to withstand the higher temperatures of the gas flow. The total temperature of the flow can be obtained using the 'mass flow parameter gasdynamic relation', by measuring the total pressure of the flow approaching the probe and the mass flow rate through the probe nozzle. When the probe is immersed in the gas stream whose temperature needs to be measured, a small amount of gas will go through the probe and will get choked at nozzle throat. The gas flowing through the probe will be cooled to lower temperature to which down stream orifice meter can measure the mass flow rate. The actual mass flow rate of the gas through probe m_a can be measured in the orifice meter by measuring upstream and differential pressure. When the flow through the probe is stopped by closing the shut off valve, the probe can act as a total pressure probe and gives the flow total pressure P_{o1}. The measured mass flow rate through the probe nozzle and the flow total pressure can be used to deduce the total temperature using mass flow parameter relation.

2. EXPERIENCE TO DATE

Perry L. Blackshear, Jr[1] measured the total temperature of the flow through the pneumatic probe. The probe consists of both the restrictions as orifices. The flow through both orifices is sonic. He compared the temperature with the iron-constantan thermocouple in the range of 422 K to 644 K indicated an error of 0.5%. In the temperature range of 1889 K to 2222 K, he compared the results with sodium D-line reversal method and obtained error of 2%.

Scadron, Marvin D [2], measured the total temperature through the pneumatic probe having the first restriction as a subsonic orifice and sonic flow converging-diverging nozzle for the second restriction. He calibrated the probe in high temperature wind tunnel by varying the temperature and gas velocity upto 1111 K. He measured temperature upto 2222 K. The maximum temperature difference between the pneumatic probe and the thermocouple is 16 K.

Havil and Rolls[3] measured the temperature using two sonic flow orifices in series. They calibrated the sonic flow orifice probe in the furnace from 300 K to 889 K. They measured the temperature upto 1778 K in afterburner exhaust.

Simmons, Frederick S, and Gwale Geoge E[4] measured the temperature using two sonic flow nozzles in series. Temperature between 889 K and 2222 K were measured using gasdynamic probe in hydrocarbon combustion Exhaust and compared with pyrometer reading.

Yang, X.L, Miller, and Hodson, H.P[5] measured the temperature using the choked nozzle in the hot flow and the orifice as the second restriction. They calibrated the probe in the range of 300 K to 900 K. The obtained the accuracy 1% at 2000 K.

In this paper, a novel gasdynamic probe having sonic nozzle as a first restriction and standard orifice meter as second restriction has been developed and calibrated.

3. GASDYNAMIC PROBE

3.1 Principle

The gasdynamic probe measures the temperature indirectly based on the aerodynamic principle. There are two popularly used configurations. The first one uses both restrictions as choking nozzle type and second one has the first restriction as choking type and second one as a non choking orifice meter type. In this case it has been chosen to develop second type. The schematic diagram of the gasdynamic probe has been shown in Fig 1 with corresponding flow stations. The first restriction (nozzle) is exposed to the exhaust gases of engines. Since the gas flow is getting choked at first restriction (nozzle), the mass flow rate through the first restriction is function of total temperature, total pressure, specific heat ratio and gas constant of the gas approaching the nozzle. From the continuity equation and under steady state condition, it can be stated that mass flow rate through the first restriction should be equal to the mass flow rate through the second restriction. The second restriction is an orifice meter, which can be used to measure the mass flow rate of the gases by measuring upstream static pressure and differential pressure across the orifice meter. The total pressure upstream of the first restriction (nozzle) can be measured by closing the shut off valve which is shown in Fig 1.

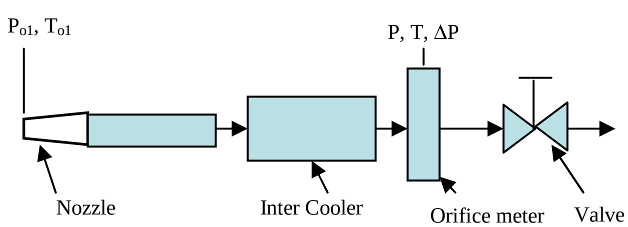

Fig. 1: Schematic diagram of gasdynamic probe

Theoretical mass flow rate equation can be written at nozzle throat under choking condition as given in equation (1).

$$m_t = A_{nt} P_{o1} \times \sqrt{\frac{\gamma}{RT_{o1}}} \times \left[\frac{2}{\gamma+1}\right]^{\gamma+1/2(\gamma-1)} \quad --(1)$$

The probe constant C is defined as the ratio of actual to theoretical mass flow rate through the probe nozzle and can be written as

$$C = \frac{m_a}{m_t} \quad --(2)$$

The equation (1) can be re-written by bringing T_{o1} to the left hand side and all other parameter to right hand side and substituting for m_t in terms of C and m_a as depicted in equation (3)

$$T_{o1} = \left[\frac{C \times A_{nt} P_{o1}}{m_a}\right]^2 \times \frac{\gamma}{R} \times \left[\frac{2}{\gamma+1}\right]^{\gamma+1/(\gamma-1)} \quad --(3)$$

In equation (3) except probe constant C all other parameters in right hand side can be measured. If C can be obtained for the particular probe by pre-calibration, the total temperature of the flow T_{o1} can be calculated based on equation (3).

The probe constant is a function of co-efficient of discharge of nozzle C_d, variation in γ and variation in nozzle throat area A_{nt}.

3.2 Construction

The essential elements of the gasdynamic probe are a converging sonic flow nozzle at leading edge of the probe, an orifice meter with pressure tapings and orifice plate, a cooling system, a shut off valve and a thermocouple after the orifice plate. The experimental probe is shown in Fig 2.

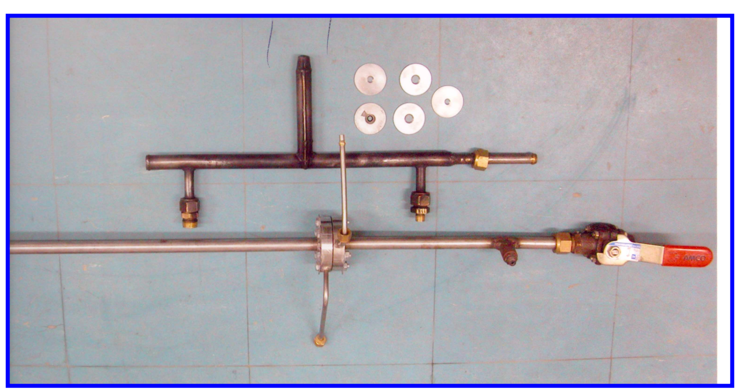

Fig. 2: Gasdynamic probe

The downstream temperature of the orifice plate is measured with a K-type thermocouple. The cooling of hot gas is achieved through two stages. The first stage is by probe cooling and second by the inter-cooling system. The total pressure P_{o1} of the flow is measured by closing the shut off valve. The diameter of the nozzle is 2.35 mm and orifice plate is 5.98 mm. The nozzle is machined through spark erosion and made of SS304. The orifice plate, cooling system and probe is made of SS304. The flow path of the hot gases and cooling water in the gasdynamic probe is shown in Fig 3. The blue arrow mark depicts the cooling water flow path and red one depicts the hot gases.

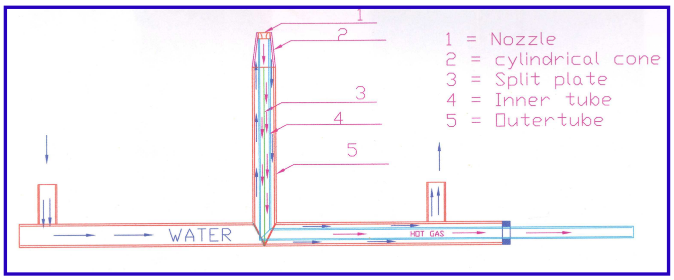

Fig. 3: The flow paths of cooling water and gas

The orifice meter in the gasdynamic probe is designed and realized based on the standard given in the Ref [6]. The advantage of making orifice meter based on the standard is the co-efficient of discharge and expansion factor of the orifice plate can be readily calculated with minimal error by the equations given in the standard. Uncertainty involved in calculating the mass flow rate is minimal compared to non-standard orifice meters.

4 EXPERIMENTAL SETUP

The schematic diagram of the experimental setup for calibrating the gasdynamic probe is shown in Fig. 4

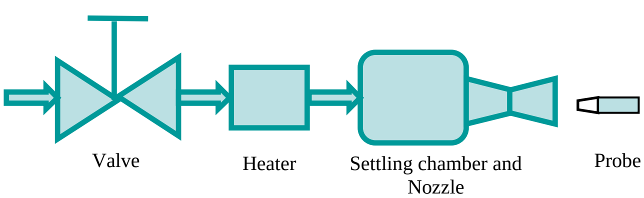

Fig. 4: Schematic diagram of the experimental setup.

The moisture free air is supplied through 200 mm diameter pipe line to the facility. The air is passed to the pre-heater through a motorized gate valve. The required pressure for the experiment is controlled through the motor operated gate valve. The pre-heater is aero-engine based kerosene fueled can combustor which heats the air up to 1000 K. A settling chamber with inner side 100 mm ceramic insulation has been installed after the pre- heater to make flow uniform. The heat loss through settling chamber walls is negligible because of the very low thermal conductivity of the insulation. The flow Mach number inside the settling chamber is in the order of 0.04. A Mach 1.8 nozzle has been directly welded to the exit of the settling chamber. The experimental setup with gasdynamic probe is shown in Fig 5.

The probe has to be moved inside the nozzle to get desired Mach numbers of the flow. The experimental setup has been instrumented for the flow total pressure and temperature. The sensors are installed in the settling chamber where very low velocity prevails. The probe has been instrumented for orifice upstream and differential pressure and orifice downstream flow temperature. The total pressure of the flow approaching the probe nozzle is measured by closing the shut off valve in the probe. The temperatures have been measured by K-type thermocouples. The pressures are measured by pressure transmitters. The pressure and temperature sensors are connected to a NI based data acquisition system and data is stored in hard disk.

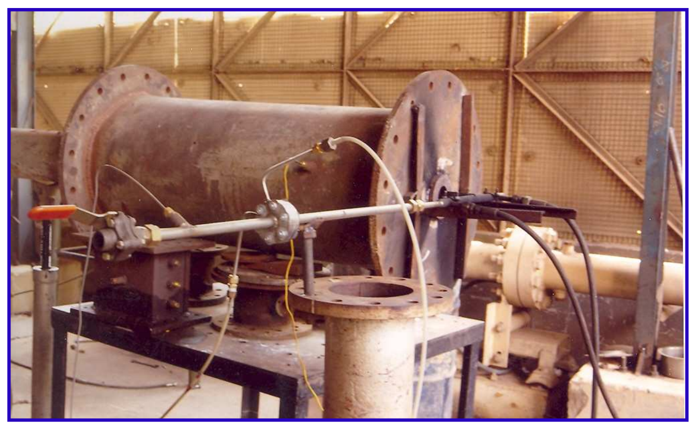

Fig. 5: Experimental setup with probe.

The sequence of experiment is as follows. The probe is fixed to appropriate position with respect to the nozzle to get desired Mach number. The air is allowed through experimental setup and pre-heater is ignited through spark plug. Pre-determined value of fuel is injected in pre-heater to achieve required temperature. Once the simulation parameters are achieved, the sensors output are recorded through data acquisition system for closed and open conditions of the shut off valve in the gasdynamic probe. The flow total temperature and pressures are varied to get matrix of data points.

Assuming negligible heat loss in the settling chamber and nozzle, it can be interpreted that temperature measured in settling chamber can be taken as $T_{o1.}$ Under the open condition of the probe shut off valve, the pressure measured at upstream of orifice meter, differential pressure across orifice meter and temperature measured at downstream of orifice meter can be used to compute the mass flow rate through the orifice meter which is equal to the mass flow rate through nozzle m_a under steady state condition. Under the closed conditions of the probe shut off valve, the orifice meter upstream pressure readings will give the stagnation pressure P_{o1} of the flow approaching the probe nozzle. Experiments were conducted by varying P_{o1} from 4 to 6 bar, T_{o1} from 300 K to 900 K and Mach number from 0.4 to 1.8.

5 RESULTS AND DISCUSSION

The probe constant C is calculated based on the equation (2). The actual mass flow rate m_a through probe nozzle can be obtained from orifice meter and theoretical mass flow rate m_t can be calculated using the equation (1). The experimental results are given below

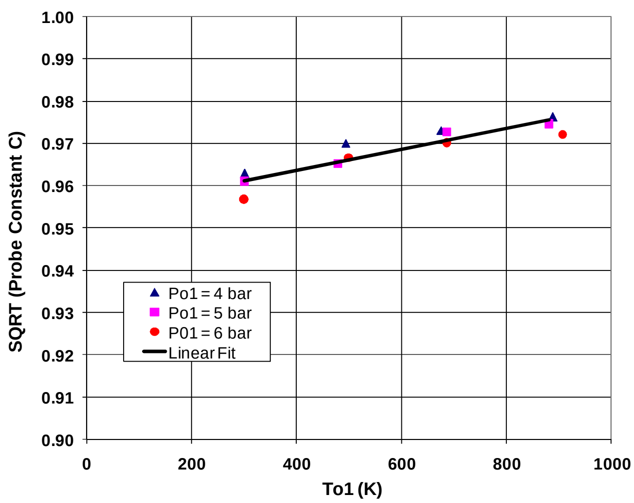

Fig. 6: Variation of C with $T_{o1;}$ Mach number 0.4

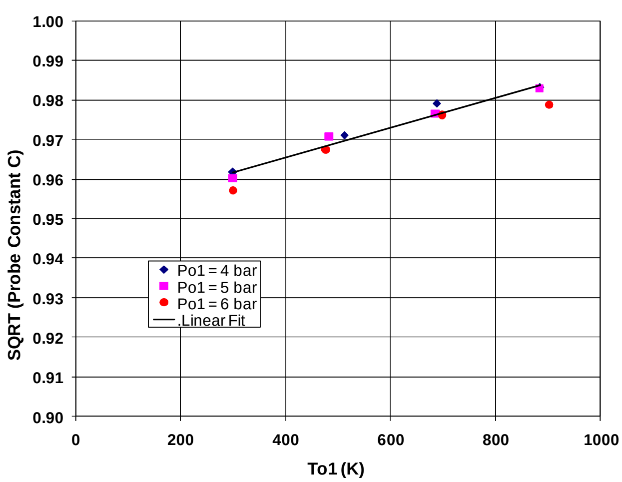

Fig. 7: Variation of C with $T_{o1;}$ Mach number 1.8

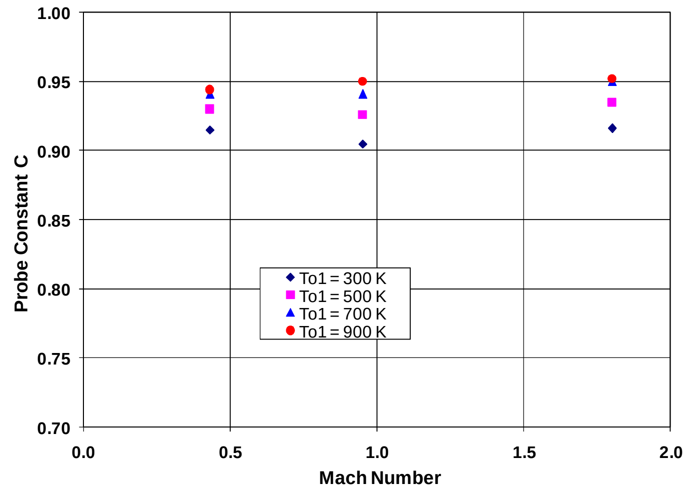

Fig. 8: Variation of C with Mach number; P_{o1} = 6 bar

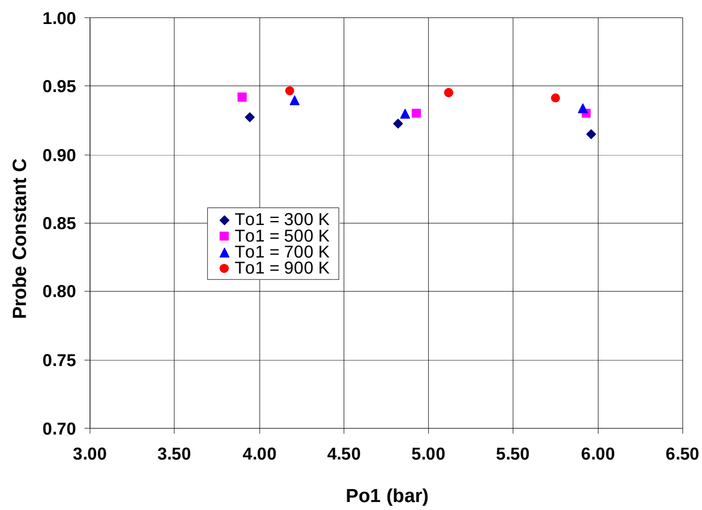

Fig. 9: Variation of C with P_{o1}; Mach number = 0.4

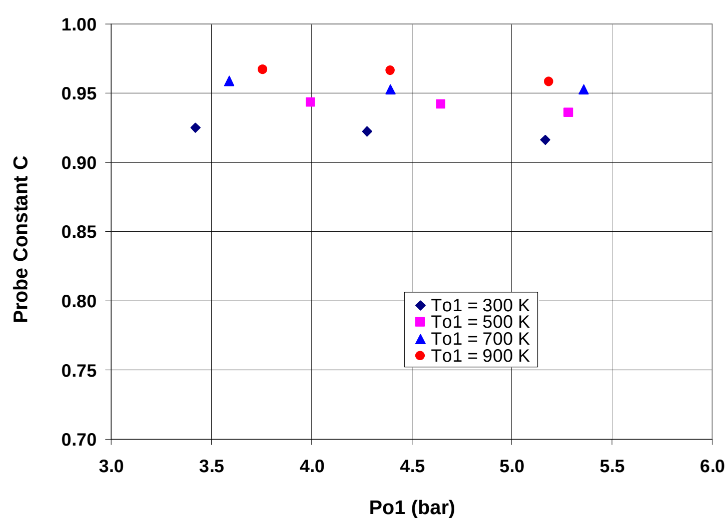

Fig. 10: Variation of C with P_{o1}; Mach number = 1.8

The variation of the probe constant C with flow total temperature T_{o1} for various flow total pressures P_{o1} and Mach numbers is shown in Fig 6 and Fig 7. It can be observed that the probe constant has second order variation with T_{o1}. The probe constant varies linearly with any change in probe nozzle throat area. The throat diameter of the nozzle will vary linearly with temperature and hence area of the nozzle throat varies in second order. So the second order variation of probe constant C with T_{o1} can be attributed to thermal expansion of the nozzle throat diameter.

Fig 8 depicts the variation of C with Mach number. Fig 9 and Fig 10 show the probe constant variation with total pressure P_{o1}. It is seen that the variation in probe constant C with Mach number and total pressure P_{o1} for a particular total temperature T_{o1} is less than 1%.

6 CONCLUSION

A gasdynamic probe for total temperature measurement in exhaust stream of air breathing engines has been designed and calibrated for various flow parameters like total temperature, total pressure and Mach number and probe constant has been obtained. It was observed that the probe constant mainly depends on the total temperature.

ACKNOWLEDGMENT

The authors wish to express their sincere thanks to Dr. J.J. Isaac, former Head, Propulsion and Wind Energy Divisions, NAL for suggesting this problem and providing all the necessary guidance and encouragement for this activity. The authors would like to thank Mr. Venu G and Mr. Pratheesh Kumar P for their help in conduction of experiments. The authors would like to thank Mr. A.T.L.N. Murthy and Mr. M Sathish Kumar for their assistance in the experimental work and documentation. The authors also wish to express their thanks to the Head Propulsion, and the Director, NAL for all their support and encouragement.

REFERENCES

[1] Blackshear and Perry L, "Sonic flow orifice temperature probe for high gas temperature measurement," NACA TN 2167, 1950.

[2] Scadron and Marvin D, "Analysis of a Pneumatic Probe for Measuring Exhaust Gas temperature with some preliminary results", NACA RM E52A11, 1952.

[3] Havill C, Dewey and Rolls L Stewart, "A sonic flow orifice probe for the in-flight measurement of temperature profiles of a jet engine exhaust with afterburning", NACA TN 3714, 1956.

[4] Simmons, Frederick S and Gwale, "Theory and design of a pneumatic probe and experimental results obtained in a high temperature gas stream" NACA TN 3893, 1957.

[5] X. L. Yang, R. J. Miller and H. P. Hodson, "A New Probe for the Measurement of High-Temperature Gases", the 16th symposium on measuring techniques in transonic and supersonic flow in cascades and turbo machines, Cambrige U.K, 2002.

[6] Measurement of Fluid Flow Using Small Bore Precision Orifice Meters ASME MFC-14M-2001.

[7] Michela Massini, Robert J. Miller, and Howard P. Hodson, "A New Intermittent Aspirated Probe for the Measurement of Stagnation Quantities in High Temperature Gases", J. Turbomach Oct 2010 Volume133, Issue4, 041022(6pages).

[8] Massini M., Miller R.J., Hodson H.P, Collings N, "A novel technique for measuring stagnation quantities and gas composition", ASME GT 2010-22920, ASME Turbo Expo, Glasgow, June 2010. .